Does DARK ENERGY Really Exist?

Maybe not.
The observations that led astronomers to deduce its existence could have another explanation: that our galaxy lies at the center of a giant cosmic void

By Timothy Clifton and Pedro G. Ferreira

In science, the grandest revolutions are often triggered by the smallest discrepancies. In the 16th century, based on what struck many of his contemporaries as the esoteric minutiae of celestial motions, Copernicus suggested that Earth was not, in fact, at the center of the universe. In our own era, another revolution began to unfold 11 years ago with the discovery of the accelerating universe. A tiny deviation in the brightness of exploding stars led astronomers to conclude that they had no idea what 70 percent of the cosmos consists of. All they could tell was that space is filled with a substance unlike any other—one that pushes along the expansion of the universe rather than holding it back. This substance became known as dark energy.

It is now over a decade later, and the existence of dark energy is still so puzzling that some cosmologists are revisiting the fundamental postulates that led them to deduce its existence in the first place. One of these is the product of that earlier revolution: the Copernican principle, that Earth is not in a central or otherwise special position in the universe. If we discard this basic principle, a surprisingly different picture of what could account for the observations emerges.

Most of us are very familiar with the idea that our planet is nothing more than a tiny speck orbiting a typical star, somewhere near the edge of an otherwise unnoteworthy galaxy. In the midst of a universe populated by billions of galaxies that stretch out to our cosmic horizon, we are led to believe that there is nothing special or unique about our location. But what is the evidence for this cosmic humility? And how would we be able to tell if we *were* in a special place? Astronomers typically gloss over these questions, assuming our own typicality sufficiently obvious to warrant no further discussion. To entertain the notion that we may, in fact, have a special location in the universe is, for many, unthinkable. Nevertheless, that is exactly what some small groups of physicists around the world have recently been considering.

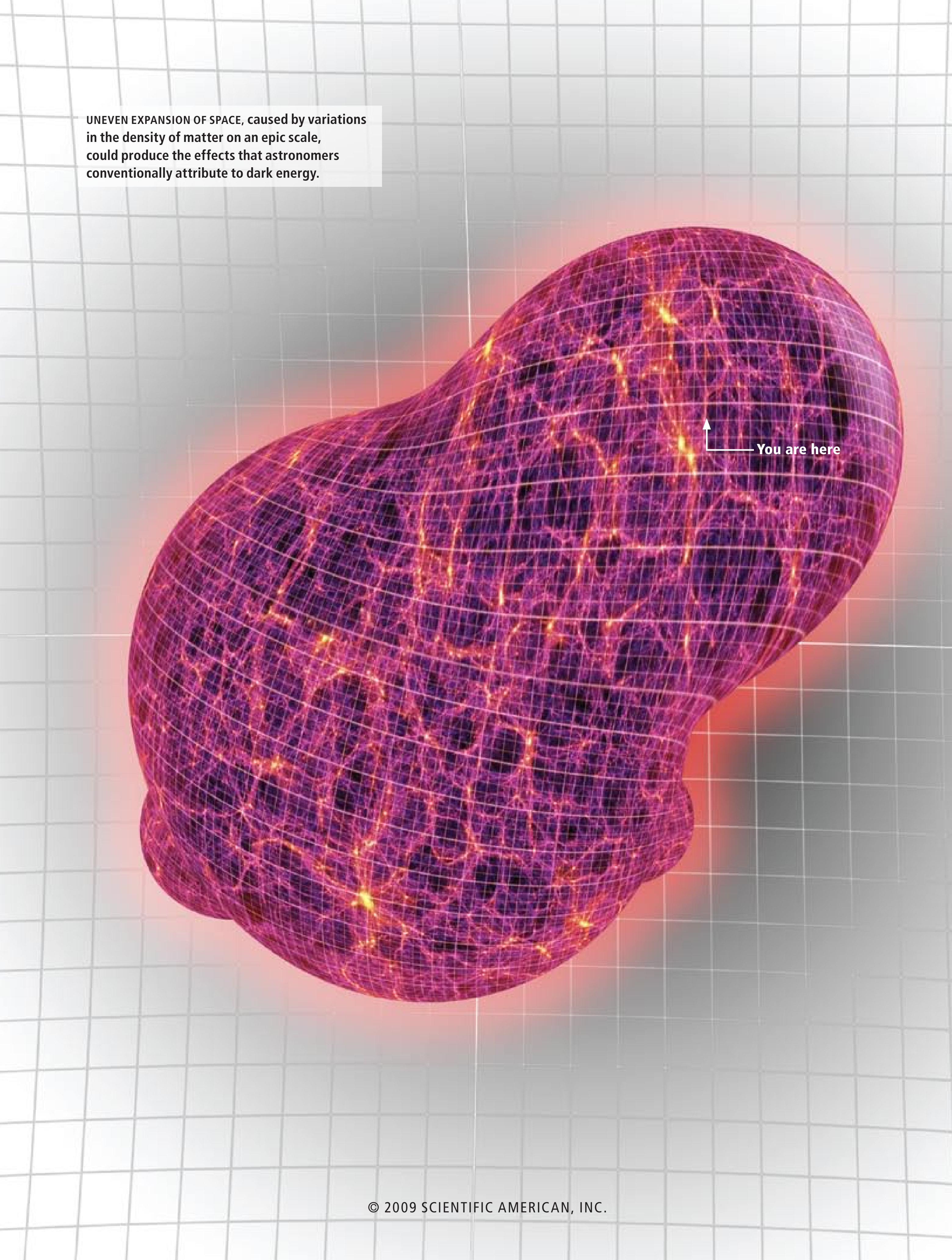
Ironically, assuming ourselves to be insignificant has granted cosmologists great explanatory power. It has allowed us to extrapolate from what we see in our own cosmic neighborhood to the universe at large. Huge efforts have been made in constructing state-of-the-art models of the universe based on the cosmological principle—a generalization of the Copernican principle that states that at any moment in time all points and directions in space look the same. Combined with our modern understanding of space, time and matter, the cosmological principle implies that space is expanding, that the universe is getting cooler and that it is populated by relics from its hot beginning—predictions that are all borne out by observations.

KEY CONCEPTS

- The universe appears to be expanding at an accelerating rate, implying the existence of a strange new form of energy—dark energy. The problem: no one is sure what dark energy is.
- Cosmologists may not actually need to invoke exotic forms of energy. If we live in an emptier-than-average region of space, then the cosmic expansion rate varies with position, which could be mistaken for a variation in time, or acceleration.
- A giant void strikes most cosmologists as highly unlikely but so for that matter does dark energy. Observations over the coming years will differentiate between the two possibilities.

—The Editors

DON DIXON



UNEVEN EXPANSION OF SPACE, caused by variations in the density of matter on an epic scale, could produce the effects that astronomers conventionally attribute to dark energy.

Astronomers find, for example, that the light from distant galaxies is redder than that of nearby galaxies. This phenomenon, known as redshift, is neatly explained as a stretching of light waves by the expansion of space. Also, microwave detectors reveal an almost perfectly smooth curtain of radiation emanating from very early times: the cosmic microwave background, a relic of the primordial fireball. It is fair to say that these successes are in part a result of our own humility—the less we assume about our own significance, the more we can say about the universe.

Darkness Closes In

So why rock the boat? If the cosmological principle is so successful, why should we question it? The trouble is that recent astronomical observations have been producing some very strange results. Over the past decade astronomers have found that for a given redshift, distant supernova explosions look dimmer than expected. Redshift measures the amount that space has expanded. By measuring how much the light from distant supernovae has redshifted, cosmologists can then infer how much smaller the universe was at the time of the explosion as compared with its size today. The larger the redshift, the smaller the universe was when the supernova occurred and hence the more the universe has expanded between then and now.

The observed brightness of a supernova provides a measure of its distance from us, which in turn reveals how much time has elapsed since it occurred. If a supernova with a given redshift looks dimmer than expected, then that supernova must be farther away than astronomers thought. Its light has taken longer to reach us, and hence the universe must have taken longer to grow to its current size [*see box on opposite page*]. Consequently, the expansion rate of the universe must have been slower in the past than previously expected. In fact, the distant supernovae are dim enough that the expansion of the universe must have accelerated to have caught up with its current expansion rate [see "Surveying Spacetime with Supernovae," by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff; Scientific American, January 1999].

This accelerating expansion is the big surprise that fired the current revolution in cosmology. Matter in the universe should tug at the fabric of spacetime, slowing down the expansion, but the supernova data suggest otherwise. If cosmologists accept the cosmological principle and assume that this acceleration happens everywhere, we are led to the conclusion that the universe must be permeated by an exotic form of energy, dark energy, that exerts a repulsive force.

Nothing meeting the description of dark energy appears in physicists' Standard Model of fundamental particles and forces. It is a substance that has not as yet been measured directly, has properties unlike anything we have ever seen and has an energy density some 10^{120} times less than we may have naively expected. Physicists have ideas for what it might be, but they remain speculative [see "The Quintessential Universe," by Jeremiah P. Ostriker and Paul J. Steinhardt; Scientific American, January 2001]. In short, we are very much in the dark about dark energy. Researchers are working on a number of ambitious and expensive ground- and space-based missions to find and characterize dark energy, whatever it may be. To many, it is the greatest challenge facing modern cosmology.

A Lighter Alternative

Confronted with something so strange and seemingly so improbable, some researchers are revisiting the reasoning that led them to it. One of the primary assumptions they are questioning is whether we live in a representative part of the universe. Could the evidence for dark energy be accounted for in other ways if we were to do away with the cosmological principle?

In the conventional picture, we talk about the expansion of the universe on the whole. It is very much like when we talk about a balloon blowing up: we discuss how big the entire balloon gets, not how much each individual patch of the balloon inflates. But we all have had experience with those annoying party balloons that inflate unevenly. One ring stretches quickly, and the end takes a while to catch up. In an alternative view of the universe, one that jettisons the cosmological principle, space, too, expands unevenly. A more complex picture of the cosmos emerges.

Consider the following scenario, first suggested by George Ellis, Charles Hellaby and Nazeem Mustapha, all at the University of Cape Town in South Africa, and subsequently followed up by Marie-Noëlle Célérier of the Paris-Meudon Observatory in France. Suppose that the expansion rate is decelerating everywhere, as matter tugs on spacetime and slows it down. Suppose, further, that we live in a gargantuan cosmic void—not a completely empty region, but one in which the average density of matter is only a half or maybe a third of the density elsewhere. The emptier a patch of space is, the less matter it contains to

COPERNICUS'S LEGACY

The Copernican principle holds that Earth does not occupy a special place in the universe. The universe has a uniform density (homogeneity) and looks the same in every direction (isotropy).

Though powerful, the principle applies only on scales much larger than a galaxy. After all, if the cosmos were completely uniform, it would be a thin gruel of atoms rather than a constellation of galaxies. Also, the principle applies in space but not in time. We live in a special era—long enough after the big bang that complex life can form but not so long that stars have all died off.

Copernicus is commonly associated with a dethroning of humanity from any position of importance. But as historian Dennis Danielson of the University of British Columbia argues, although pre-Copernican Europeans placed Earth at the center of the universe, they did not consider the center a position of importance but quite the opposite—as Galileo put it, "the sump where the universe's filth and ephemera collect."

POLISH SCHOOL/BRIDGEMAN ART LIBRARY/GETTY IMAGES (*Copernicus*)

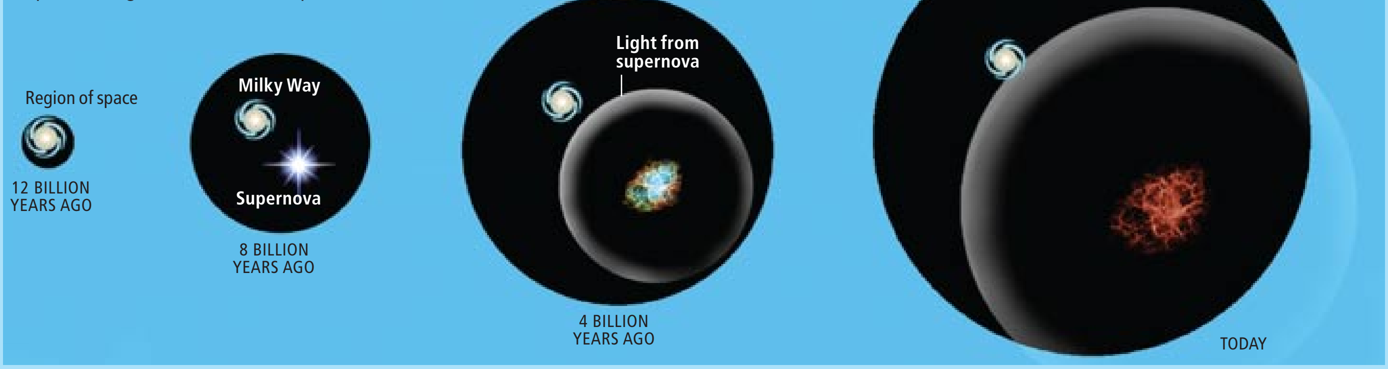
[THE BASICS]

Three Ways of Expanding a Universe

Astronomers have found that distant supernovae explosions are dimmer than expected. To see what this discovery means for cosmic expansion, consider a region of space that encompasses a supernova and our Milky Way galaxy. Over time this region gets bigger as the fabric of space stretches like a rubber sheet. The supernova goes off when the universe is about half its current size (which occurs at different times depending on whether the expansion is decelerating or accelerating). Light from the explosion spreads out and eventually reaches us on the outskirts of the Milky Way.

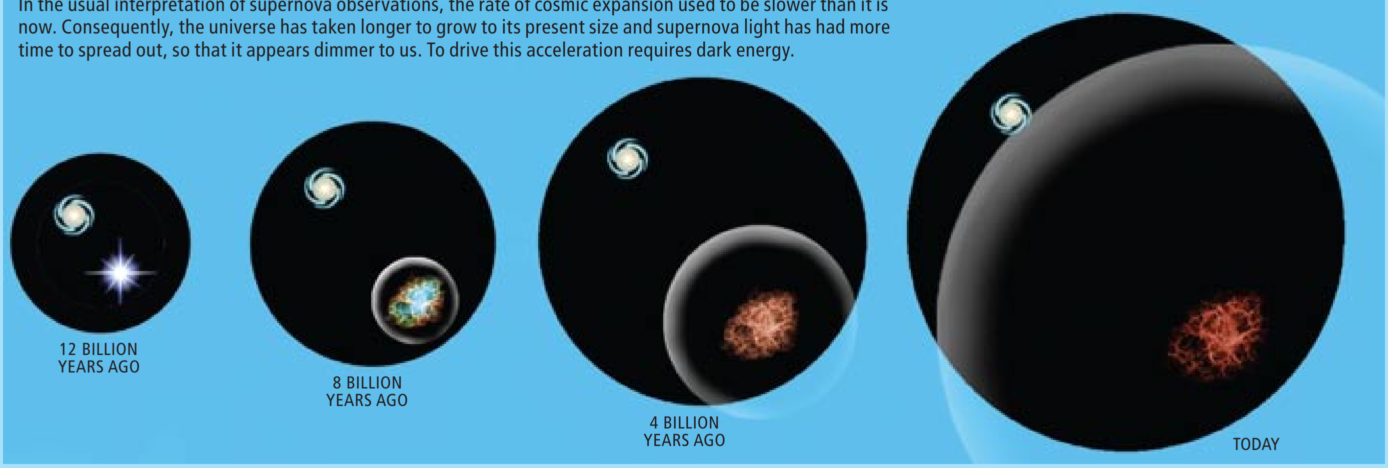
OLD VIEW: EXPANSION IS DECELERATING

Prior to 1998, most cosmologists assumed that cosmic expansion was slowing down over time. In each time increment, the region of space increases in size by a diminishing factor. They based their expectations of supernova brightness on this assumption.



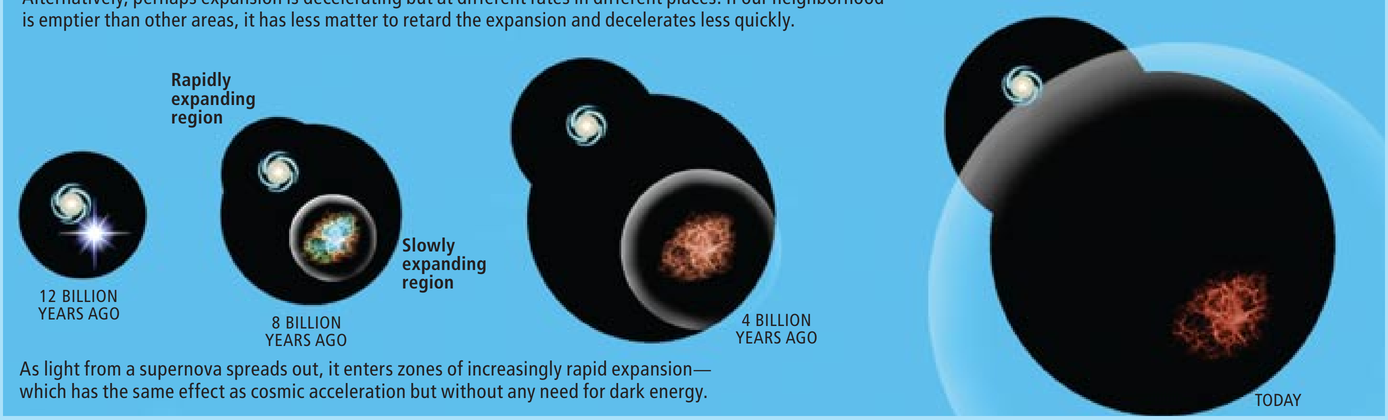
SCENARIO 1: EXPANSION IS ACCELERATING

In the usual interpretation of supernova observations, the rate of cosmic expansion used to be slower than it is now. Consequently, the universe has taken longer to grow to its present size and supernova light has had more time to spread out, so that it appears dimmer to us. To drive this acceleration requires dark energy.



SCENARIO 2: UNIVERSE IS INHOMOGENEOUS

Alternatively, perhaps expansion is decelerating but at different rates in different places. If our neighborhood is emptier than other areas, it has less matter to retard the expansion and decelerates less quickly.



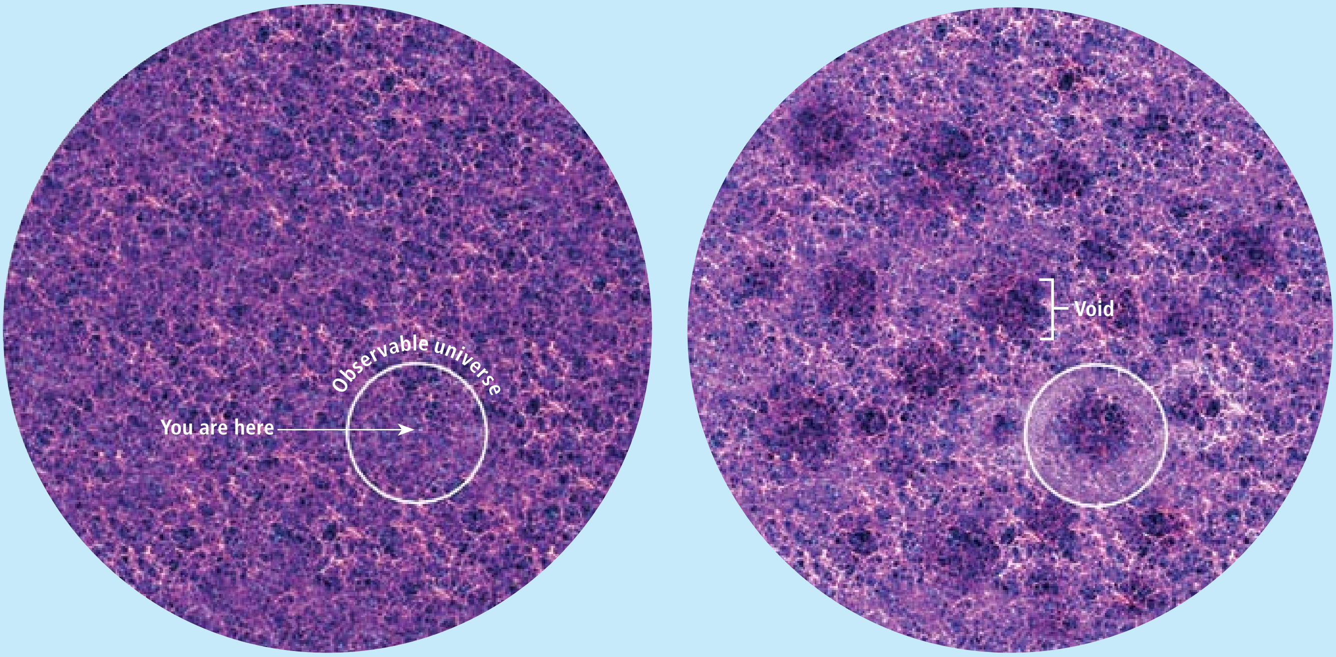
As light from a supernova spreads out, it enters zones of increasingly rapid expansion—which has the same effect as cosmic acceleration but without any need for dark energy.

DON DIXON

[THE BIG PICTURE]

A Special Place for Us

In his *Hitchhiker's Guide to the Galaxy* series of novels, Douglas Adams imagines a torture device that drives people insane by showing them the utter insignificance of their place in the universe. One would-be victim emerges unscathed when it turns out that the universe does, in fact, revolve around him. In a case of life imitating art, many cosmologists are investigating whether our planet indeed has a special place within the grand scheme of things.



HOMOGENEOUS UNIVERSE: OUR LOCATION IS TYPICAL
In the standard view, galaxies are lined up in a spidery pattern, but overall space looks much the same everywhere, and Earth's position is nothing special.

INHOMOGENEOUS UNIVERSE: OUR LOCATION IS SPECIAL
Alternatively, the density of matter could vary on large scales, and Earth may lie at or near the center of a relatively less dense region, or void.

DON DIXON

slow down the expansion of space; accordingly, the local expansion rate is faster within the void than it is elsewhere. The expansion rate is fastest at the very center of the void and diminishes toward the edge, where the higher-density exterior begins to make itself felt. At any given time different parts of space will expand at different rates, like the unevenly inflated party balloon.

Now imagine supernovae exploding in different parts of this inhomogeneous universe, some close to the center of the void, others nearer the edge and some outside the void. If we are near the center of the void and a supernova is farther out, space expands faster in our vicinity than it does at the location of the supernova. As light from the supernova travels toward us, it passes through regions that are expanding at ever faster rates. Each region stretches the light by a certain amount as it passes though, and the cumulative effect produces the redshift we observe. Light traveling a given distance is redshifted by less than it would be if the whole universe expanded at our local rate. Conversely, to achieve a certain redshift in such a universe, the light has to travel a greater distance than it would in a uniformly expanding universe, in which case the supernova has to be farther away and therefore appear dimmer.

Another way to put it is that a variation of expansion rate with position mimics a variation in time. In this way, cosmologists can explain the unexpected supernova observations without invoking dark energy. For such an alternative explanation to work, we would have to live in a void of truly cosmic proportions. The supernova observations extend out to billions of light-years, a significant fraction of the entire observable universe. A void would have to be of similar size. Enormous by (almost) anyone's standards.

A Far-fetched Possibility

So how outlandish is this cosmic void? At first glance, very. It would seem to fly in the face of the cosmic microwave background, which is uniform to one part in 100,000, not to mention the apparently uniform distribution of galaxies [see "Reading the Blueprints of Creation," by Michael A. Strauss; SCIENTIFIC AMERICAN, February 2004]. On closer inspection, however, this evidence may not be so conclusive.

The uniformity of the relic radiation merely requires the universe to look nearly the same in every direction. If a void is roughly spherical and if we lie reasonably close to its center, these observations do not necessarily preclude it. In addition, the cosmic microwave background has some anomalous features that could potentially be explained by large-scale inhomogeneity [*see box on next page*].

As for the galaxy distribution, existing surveys do not extend far enough to rule out a void of the size that would mimic dark energy. They identify smaller voids, filaments of matter and other structures hundreds of millions of light-years in size, but the putative void is an order of magnitude larger. A lively debate is now under way in astronomy as to whether galaxy surveys corroborate the cosmological principle. A recent analysis by David Hogg of New York University and his collaborators indicates that the largest structures in the universe are about 200 million light-years in size; on larger scales, matter appears smoothly distributed, in accordance with the principle. But Francesco Sylos Labini of the Enrico Fermi Center in Rome and his colleagues argue that the largest structures discovered so far are limited only by the size of the galaxy surveys that found them. Still larger structures might stretch beyond the scope of the surveys.

By analogy, suppose you had a map showing a region 10 miles wide, on which a road stretched from one side to the other. It would be a mistake to conclude that the longest possible road is 10 miles long. To determine the length of the longest road, you would need a map that clearly showed the end points of all roads, so that you would know their full extent. Similarly, astronomers need a galaxy survey that is larger than the biggest structures in the universe if they are to prove the cosmological principle. Whether surveys are big enough yet is the subject of the debate.

For theorists, too, a colossal void is difficult to stomach. All available evidence suggests that galaxies and larger structures such as filaments and voids grew from microscopic quantum seeds that cosmic expansion enlarged to astronomical proportions, and cosmological theory makes firm predictions for how many structures should exist with a certain size. The larger a structure is, the rarer it should be. The probability of a void big enough to mimic dark energy is less than one part in 10^{100}. Giant voids may well exist out there, but the chance of our finding one in our observable universe would seem to be tiny.

Still, there is a possible loophole. In the early 1990s one of the authors of what is now the standard model of the early universe, Andrei Linde, and his collaborators at Stanford University showed that although giant voids are rare, they expand faster early on and come to dominate the volume of the universe. The probability of observers finding themselves in such a structure may not be so tiny after all. This result shows that the cosmological principle (that we do not live in a special place) is not always the same thing as the principle of mediocrity (that we are typical observers). One can, it seems, be both typical and live in a special place.

Testing the Void

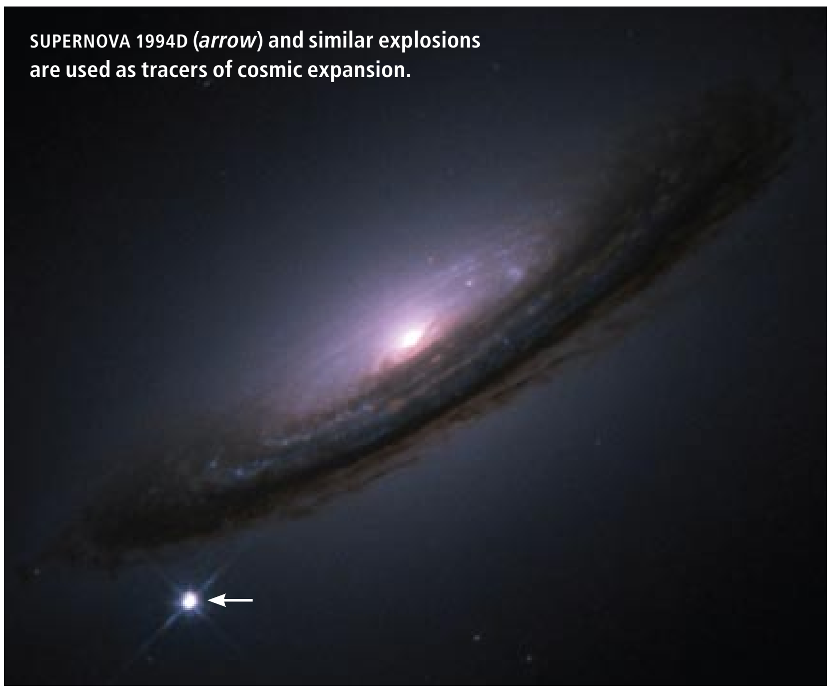
What observations could tell whether the expansion of the universe is driven by dark energy or whether we are living in a special place, such as at the center of a giant void? To test for the presence of a void, cosmologists need a working model of how space, time and matter should behave in its vicinity. Just such a model was formulated in 1933 by Abbé Georges Lemaître, independently rediscovered a year later by Richard Tolman and further developed after World War II by Hermann Bondi. The universe they envisaged had expansion rates that depended not only on time but also on distance from a specific point, just as we now hypothesize.

With the Lemaître-Tolman-Bondi model in hand, cosmologists can make predictions for a

NO A-VOIDING IT

Although a cosmic void mimics dark energy, the match is not exact. Upcoming observations will look for telltale differences.

- Additional supernova observations will pin down the expansion rate and check whether it varies with position, as a void model predicts.
- Galaxy clusters reflect light and, in effect, let us view our cosmic neighborhood in the mirror. If we live in a void, we should be able to see it.
- Galaxies and galaxy clusters evolve at a pace that depends on the expansion rate at their location and therefore on the presence of a void.
- Neutrinos left over from the primordial universe could reveal a void.



SUPERNOVA 1994D (*arrow*) and similar explosions are used as tracers of cosmic expansion.

NASA/ESA, HUBBLE KEY PROJECT TEAM AND HIGH-Z SUPERNOVA SEARCH TEAM range of observable quantities. To begin, consider the supernovae that first led to the inference of dark energy. The more supernovae that astronomers observe, the more accurately they can reconstruct the expansion history of the universe. Strictly speaking, these observations cannot ever rule out the void model, because cosmologists could re-create any set of supernova data by choosing a suitably shaped void. Yet for a void to be completely indistinguishable from dark energy, it would have to have some very strange properties indeed.

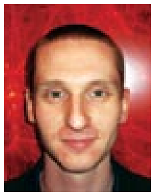
The reason is that the putative accelerating expansion occurs right up to the present moment. For a void to mimic it exactly, the expansion rate must decrease sharply away from us and in every direction. Therefore, the density of matter and energy must increase sharply away from us in every direction. The density profile must look like an upside-down witch's hat, the tip of which corresponds to where we live. Such a profile would go against all our experience of what structures in the universe look like: they are usually smooth, not pointy. Even worse, Ali Vanderveld and Éanna Flanagan, both then at Cornell University, showed that the tip of the hat, where we live, would have to be a singularity, like the ultradense region at the center of a black hole.

If, however, the void has a more realistic, smooth density profile, then a distinct observational signature presents itself. Smooth voids still produce observations that could be mistaken for acceleration, but their lack of pointyness means that they do not reproduce *exactly* the same results as dark energy. In particular, the apparent rate of acceleration varies with redshift in a telltale way. In a paper with Kate Land, then at the University of Oxford, we showed that several hundred new supernovae, on top of the few hundred we currently have, should be enough to settle the issue. Supernova-observing missions stand a very good chance of achieving this goal soon.

Supernovae are not the only observables available. Jeremy Goodman of Princeton University suggested another possible test in 1995 using the microwave background radiation. At the time, the best evidence for dark energy had not yet emerged, and Goodman was not seeking an explanation for any unexplained phenomena but proof of the Copernican principle itself. His idea was to use distant clusters of galaxies as mirrors to look at the universe from different positions, like a celestial dressing room. Galaxy clusters reflect a small fraction of the microwave radiation that hits them. By carefully measuring the spectrum of this radiation, cosmologists could infer some aspects of what the universe would look like if viewed from one of them. If a shift of viewpoint changed how the universe looked, it would be powerful evidence for a void or a similar structure.

Two teams of cosmologists recently put this idea to the test. Robert Caldwell of Dartmouth

[THE AUTHORS]




Timothy Clifton and **Pedro G. Ferreira** are cosmologists at the University of Oxford. Both study the physics of the early universe and potential modifications to Einstein's general theory of relativity. Clifton, a keen oenophile, says his true interest in life is Burgundy wine. Ferreira is the author of a popular-level astronomy book, *The State of the Universe*, runs a program for artists in residence at Oxford, and participates in various projects to support science education in Africa.

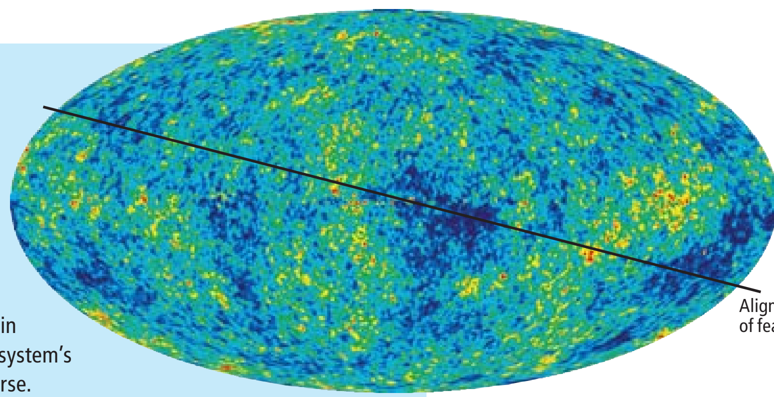
Surrender to the Void

Most suggestions that we live in a cosmic void place us at its center, but what if we lived away from the middle? The universe would then look slightly lopsided. Håvard Alnes and Morad Amarzguioui, both at the University of Oslo, have shown that the cosmic microwave background radiation would look slightly hotter in one direction than in the other. Such an asymmetry, called a dipole, has indeed been observed in the microwave background. It is usually attributed to our solar system's motion through space but could also be a sign of a lumpy universe.

Furthermore, small fluctuations in the microwave background appear to align in a specific direction—dubbed the "axis of evil" by João Magueijo and Kate Land, both then at Imperial College London [see "Is the Universe Out of Tune?" by Glenn D. Starkman and Dominik J. Schwarz; SCIENTIFIC AMERICAN, August 2005]. This alignment picks out a preferred direction in the sky, which, though hard to imagine in a Copernican universe, might be explained in terms of our displacement from the center of a void. A preferred direction would also have other effects, such as large-scale coherent motions of galaxies and galaxy clusters. Several researchers have claimed to have detected such a "dark flow," but it remains controversial.

Although it is tempting to attribute these anomalies to a giant void, this explanation does not really hold together. For a start, these effects each pick out different directions. Furthermore, the strength of the cosmic dipole would suggest that we are only about 50 million light-years from the center, which is only a very small fraction of the total size of the putative void.

—T.C. and P.G.F.



AXIS OF EVIL, **an alignment of features in the cosmic microwave background radiation, could be a sign that we live in an inhomogeneous universe.**

College and Albert Stebbins of the Fermi National Accelerator Laboratory in Batavia, Ill., studied precise measurements of distortions in the microwave background, and Juan García-Bellido of the University of Madrid and Troels Haugbølle of the University of Aarhus in Denmark looked at individual clusters directly. Neither group detected a void; the best the researchers could do was to narrow down the properties that such a void could have. The Planck Surveyor satellite, scheduled for launch this month, should be able to place stronger limits on the void properties and maybe rule out a void altogether.

A third approach, advocated by Bruce Bassett, Chris Clarkson and Teresa Lu, all at the University of Cape Town, is to make independent measurements of the expansion rate at different locations. Astronomers usually measure expansion rates in terms of redshift, which is the cumulative effect of the expansion of all regions of space between a celestial body and us. By lumping all these regions together, redshift cannot distinguish a variation of expansion rate in space from a variation in time. It would be better to measure the expansion rate at specific spatial locations, separating out the effects of expansion at other locations. That is a difficult proposition, though, and has yet to be done. One possibility is to observe how structures form at different places. The formation and evolution of galaxies and galaxy clusters depend, in large part, on the local rate of expansion. By studying these objects at different locations and accounting for other effects that play a role in their evolution, astronomers may be able to map out subtle differences in expansion rate.

A Not So Special Place

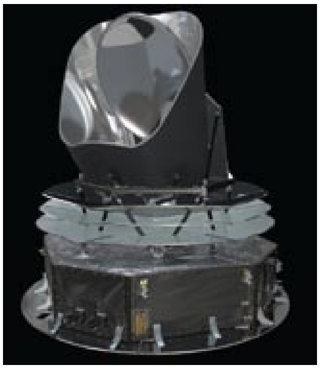
The possibility that we live in the middle of a giant cosmic void is an extreme rejection of the cosmological principle, but there are gentler possibilities. The universe could obey the cosmological principle on large scales, but the smaller voids and filaments that galaxy surveys have discovered might collectively mimic the effects of dark energy. Tirthabir Biswas and Alessio Notari, both at McGill University, as well as Valerio Marra and his collaborators, then at the University of Padua in Italy and the University of Chicago, have studied this idea. In their models, the universe looks like Swiss cheese—uniform on the whole but riddled with holes. Consequently, the expansion rate varies slightly from place to place. Rays of light emitted by distant supernovae travel through a multitude of these small voids before reaching us, and the variations in the expansion rate tweak their brightness and redshift. So far, however, the idea does not look very promising. One of us (Clifton), together with Joseph Zuntz of Oxford, recently showed that reproducing the effects of dark energy would take lots of voids of very low density, distributed in a special way.

Another possibility is that dark energy is an artifact of the mathematical approximations that cosmologists routinely use. To calculate the cosmic expansion rate, we typically count up how much matter a region of space contains, divide by the volume of the region and arrive at the average energy density. We then insert this average density into Einstein's equations for gravity and determine the averaged expansion rate of the universe. Although the density varies from place to place, we treat this scatter as small fluctuations about the overall average.

The problem is that solving Einstein's equations for an averaged matter distribution is *not* the same as solving for the real matter distribution and then averaging the resulting geometry. In other words, we average and then solve, when really we should solve and then average.

Solving the full set of equations for anything even vaguely approximating the real universe is unthinkably difficult, and so most of us resort to the simpler route. Thomas Buchert of the University of Lyon in France has taken up the task of determining how good an approximation it really is. He has introduced an extra set of terms into the cosmological equations to account for the error introduced by averaging before solving. If these terms prove to be small, then the approximation is good; if they are large, it is not. The results so far are inconclusive. Some researchers have suggested that the extra terms may be enough to account for dark energy entirely, whereas others claim they are negligible.

Observational tests to distinguish between dark energy and the void models are set to be carried out in the very near future. The Supernova Legacy Survey, led by Pierre Astier of the University of Paris, and the Joint Dark Energy Mission, currently under development, should pin down the expansion history of the universe. The Planck Surveyor satellite and a variety of ground-based and balloon-borne instruments will map out the microwave background in ever greater detail. The Square Kilometer Array, a gigantic radio telescope planned for 2020, will supply us with a survey of all the galaxies within our observable horizon. This revolution in cosmology began a decade ago, and it is far from over. ■



ESA/AOES MEDIALAB

WALKING THE PLANCK

The latest spacecraft to measure the cosmic microwave background radiation, the European Space Agency's Planck Surveyor, is scheduled to launch this month.

Planck should provide a complete inventory of fluctuations in the temperature of the microwave background, thereby completing an observational effort that began in the 1960s. These fluctuations reveal what the universe looked like at the tender age of 400,000 years and how it has grown since then. It could tell us whether we live in a giant void.

Planck will also measure fluctuations in the polarization (or directionality) of the radiation, which could reveal whether gravitational waves coursed through the ancient universe as a result of high-energy processes a fraction of a second after the big bang—or even before it.

➥ MORE TO EXPLORE

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